# Frontiers of Seismology

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# Frontiers of Seismology

**MEETING REPORT Frontiers of Seismology was a wide-ranging, cross-disciplinary meeting held in Edinburgh in April this year. Susanne Sargeant, Lars Ottemöller, Brian Baptie, Andy Bell, Andrew Curtis and Ian Main join forces to give a flavour of the meeting and the new strengths it revealed in seismology in the UK.**

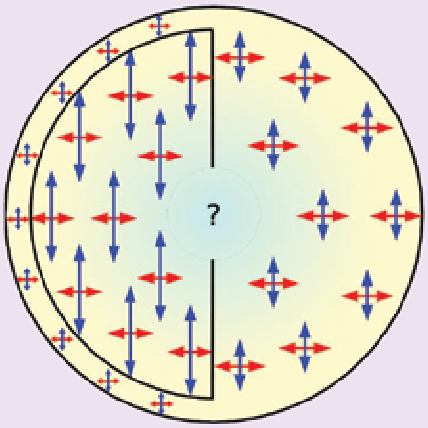
Levels of seismicity in the UK may be low by global standards (around 150 earthquakes are detected per year) but the country is home to a vibrant and diverse seismological research community. Fields studied range from the workings of the inner core to nascent continental rifting in Afar, from the study of ancient subduction zones to near-surface Earth-resources exploration and imaging, from theoretical seismology to hazard and the impact of earthquakes on buildings and people. Recent improvements in seismic acquisition and processing for industrial exploration are impressive, and earthquake seismic monitoring continues to improve at a pace. This trend can be expected to lead to more detailed information about earthquake sources and Earth structure in the future. There are many frontiers being explored with an increasing emphasis on multidisciplinary collaborative working and finding novel ways to apply existing knowledge.

The aims of the Frontiers of Seismology meeting were to bring research groups together, to assess the state of UK-based seismological research, and to discuss the medium- and long-term evolution of science that crosses boundaries of traditional seismological research. And so, on 2 and 3 April 2009, 105 scientists from universities, research institutes and industry gathered at Our Dynamic Earth in Edinburgh.

## Diverse community

The sample of current research that emerged showed a diverse community in seismology, united by the need to become more visible in UK research as a whole. Better data, technological advances and interdisciplinary collaboration in new fields were identified as necessary to push back the frontiers of seismological research; indeed, interdisciplinary research emerged as the key process for tackling complex problems and applying knowledge in new fields. Frontiers of Seismology succeeded in bringing together researchers from fields with distinct and often isolated meetings and cultures – a model for building collaborative networks for the future.

**David Kerridge** (British Geological Survey) and **Phil Christie** (Schlumberger Cambridge Research and President of the European Association for Geoscientists and Engineers) jointly opened the meeting. David highlighted that




1: Cartoon of velocity anisotropy in Earth's inner core. (From Jessica Irving's University of Cambridge PhD thesis 2009)

funding for the Natural Environment Research Council (NERC) research programmes is set to grow. These programmes explicitly address the scientific challenges and priorities identified by the NERC Next Generation Science for Planet Earth 2007–2012 strategy, and are of considerable consequence to the British research community. Phil demonstrated the enormous amount that academic and industrial research communities gain by working together, highlighting successful examples of the plate margin imaging projects on the Faroe Islands Atlantic passive volcanic margin and on the Sumatra subduction zone.

There followed a packed programme including 32 talks and 35 posters on a range of topics, which were divided into two themes: Earth Imaging and Earth Dynamics. These themes were themselves subdivided into sessions, and session chairs reported back on what they saw as the key themes to emerge at the end of each day. With this approach, we aimed to give participants an opportunity to ask questions relating to specific presentations as well as to discuss more general issues. Our aim in this article is to summarize some of the research presented, along with some of the more generic topics discussed. The work presented represents the contributions of a large number of people and for the sake of brevity we give the speakers' names and affiliations only. Full details are available on the Frontiers of Seismology website (http://www.earthquakes.bgs.ac.uk/seis09).

## Earth imaging

While travelling from the source to the receiver, seismic waves are affected by the physical properties of the medium through which they pass. The goal of seismic imaging is to unravel recordings of earthquakes, explosions and even background noise to image the Earth's subsurface and estimate its physical properties. Advances in seismic imaging are achieved through data improvements in terms of coverage and quality, through improved data-processing power and novel techniques, and also from theoretical developments allowing new data types to be employed. In the first talk of the meeting, **John Woodhouse** (University of Oxford) gave an overview of global seismic tomography showing how surface wave tomography, travel time tomography and analysis of free Earth oscillations can be combined to produce spatially averaged images of the global interior of the Earth. The results reveal large-scale velocity and temperature variations that correspond to thick continental keels and subduction into the deep mantle.

**Jessica Irving** (University of Cambridge) showed how seismic body waves and normal mode oscillations can be used to image the inner core. Jessica's results confirm anisotropy in the inner core and suggest that it can be divided into anisotropic and isotropic hemispheres (figure 1), roughly eastern and western respectively with boundaries at 10°E and 150°W, which has important implications for our understanding of the geophysical processes that occur there. Much of the Earth's lower mantle appears to be relatively homogeneous, but a few hundred kilometres above the core–mantle boundary there is a highly heterogeneous zone known as D″, which is associated with large increases in S-wave velocity. Here, anisotropy is associated with mineral changes that can be used to infer the presence of colder than average regions deep beneath subduction zones, as **Andy Nowacki** (University of Bristol) showed for the Caribbean and Central America using data from very deep earthquakes. **Sebastian Rost** (University of Leeds) is using array observations of high-frequency scattered waves to study fine-scale heterogeneities of the Earth's deep interior. These scattered waves are sensitive to small-scale variations in velocity and density, and Sebastian's results show that there is strong scattering in certain regions of the lowermost mantle, which may correspond to remnants of subducted crust or partial melt inclusions.

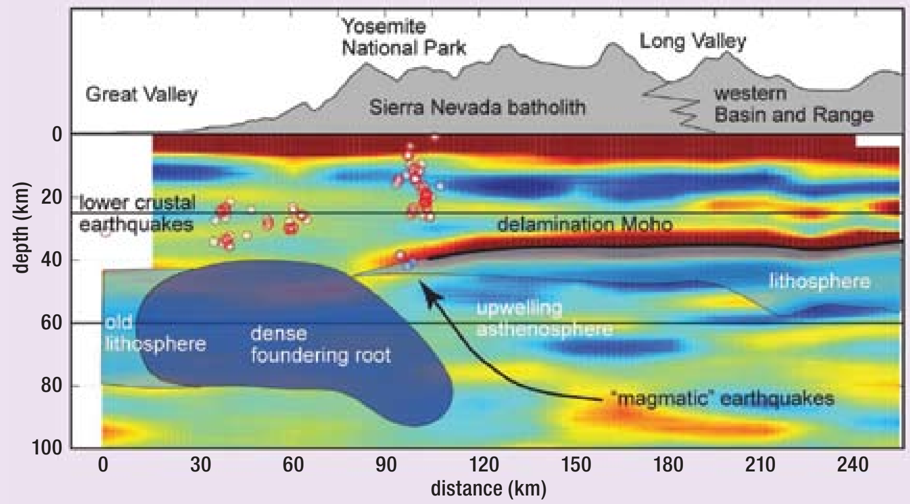
In the lower crust and mantle, seismic anisotropy is normally attributed to crystal orientation. However, anisotropy can also be generated by melt-filled pockets or inclusions. **Mike Kendall** (University of Bristol) presented anisotropy observations from two very different tectonic environments: the Archean Western Superior province of the Canadian Shield, and the Main Ethiopian Rift. Focusing on the frequency dependence of anisotropy as an indicator of the presence of fluid-filled inclusions, Mike showed that there is no obvious frequency dependence in the cratonic region. In contrast, the data from the rift show strong frequency dependence, indicating that there is melt present in inclusions of the order of centimetres in size. **Mark Chapman** (British Geological Survey) presented a theory for modelling seismic wave propagation across multi-scaled porosity and fractures containing more than one fluid, of great importance for the hydrocarbon exploration industry. Mark's model predicts frequency-dependent seismic attenuation using detailed rock physics, allowing observed frequency-dependence and attenuation to be used to constrain subsurface rock properties. **Ross Haacke** (Royal Holloway University of London) showed that significant seismic anisotropy occurs within 30 m of the seabed, suggesting that this material is not the "muddy soup" that one might expect: anisotropy implies that either aligned cracks or grains are present. These results are potentially useful for engineers and scientists interested in shallow geotechnical problems such as the design and installation of seabed infrastructure. **Saskia Goes** (Imperial College London) presented their interpretation of the seismic models through a thermo-chemical model for the mantle. The seismic velocities are computed for a set of thermal and chemical models using thermodynamics. Some features in the seismic model remain unexplained despite the uncertainties, and it remains a challenge to build a single thermo-chemical structure that explains available data.

Low shear wave velocities ($v_s$) observed beneath oceanic spreading ridges and plates are commonly attributed to the presence of melt but, as **Keith Priestley** (University of Cambridge) argued, the amount of melt in these regions is not sufficient to explain the observed velocities. However, temperature does have a significant effect and Keith presented an empirical relation for $v_s$ developed by combining thermal models of the Pacific lithosphere and pressure and temperature data with 3D models of $v_s$. They used this relationship to estimate lithospheric thickness and verified their results from the distribution of diamond-bearing kimberlites.

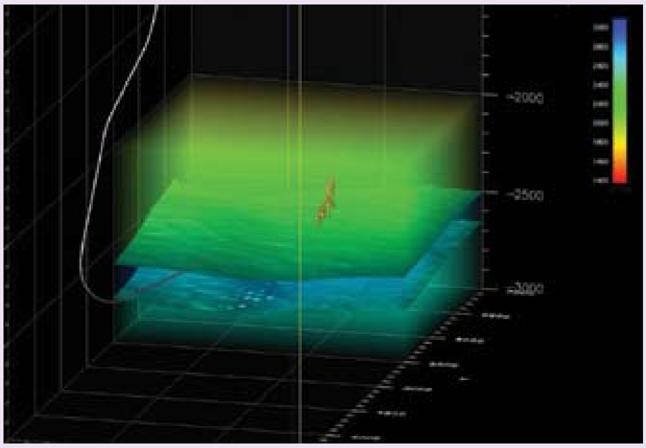
Despite the great progress made in mapping lateral variations in seismic velocities in the lithosphere and asthenosphere, there are still significant uncertainties associated with the results. **Ana Fereira** (University of East Anglia) is investigating radial anisotropy in the upper mantle and showed the effect that different crustal models can have on the results, highlighting the importance of establishing the robustness of results before interpreting them. Constraining the depth distribution of seismic anisotropy has also proved particularly difficult and **Sergei Lebedev** (Dublin Institute for Advanced Studies) showed how greater robustness and resolution can be achieved with data from dense modern broadband networks. Layering in the anisotropic fabric of the lithosphere sheds light on the evolutionary history of the lower crust and mantle. The crust and lower mantle beneath the Sierra Nevada has been investigated using receiver function analysis and shear wave splitting and these results were presented by **Ian Bastow** (University of Bristol). The results reveal a marked change in character of the Moho between the eastern Sierras, where a sharp transition is seen, to the western Sierras, where the transition is gradational (figure 2).

Our knowledge of the subsurface is limited by where instrumentation can be deployed so local measurements from areas of great geological and tectonic interest such as mid-ocean ridges and subduction zones are few and far between. **Andrew Curtis** (University of Edinburgh) presented a new method of seismic interferometry in which a virtual seismogram recording can be made in the Earth's deep subsurface at the location of any well-recorded earthquake hypocentre. This recording is synthesized from real earthquake recordings made on the surface. Andrew illustrated this by turning two earthquakes in southwest USA into virtual subsurface seismometers, and used them to record seismograms from other nearby earthquakes.

The common outcome from the session on Earth imaging was that improvements are not only achieved from improved data sets, but also through new techniques. An impressive illustration of what can be achieved was given by **Johan Robertsson** (Schlumberger Cambridge Research). In the search for hydrocarbons, great computational and data acquisition resources are available, and 3D or 4D (3D plus temporal dependence) seismic images are often the minimum level of subsurface information required by industry before significant drilling activity takes place. Johan showed how some of the traditional limitations of subsurface imaging

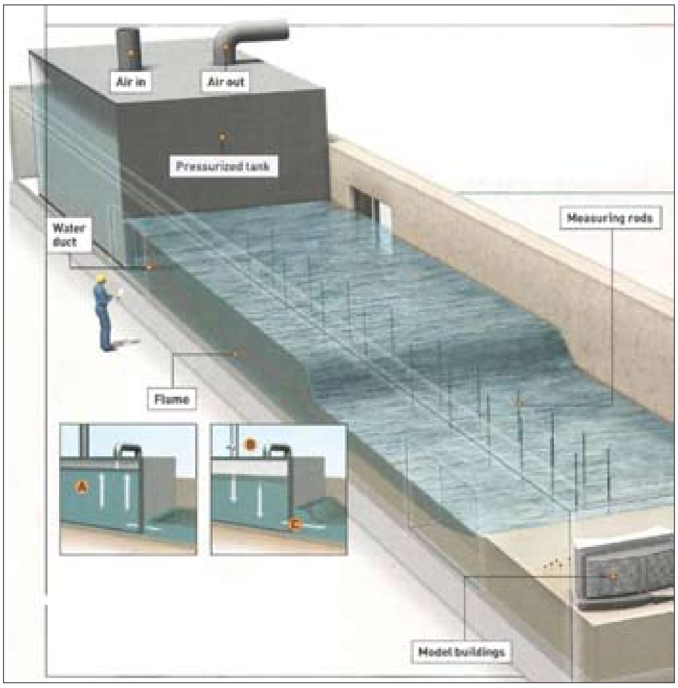



**2: Structure beneath the Sierra Nevada, highlighting the complexities of the crust–mantle boundary revealed by receiver function analysis and shear wave splitting. (Bastow)**




**3: Perspective view showing locations of events (red circles) detected during hydraulic fracturing in a North Sea oil reservoir. The background velocity model and path of the inject well are also shown for reference. (K Chambers, O Barkved and J-M Kendall 2009 *Imaging induces seismicity with the LoFS permanent sensor surface array* in prep.)**

**4: Glacier seismic and GPS station on the West Antarctic Ice Sheet. (A Smith)**




**5: Modelling tsunamis and warning systems. (Anthony Hardwick)**

can now be overcome through better data and processing facilities, and in particular full waveform inversion for subsurface structure and properties is becoming a commercial reality within the exploration industry.

## Earth dynamics

On the second day, attention turned to earthquakes, from the smallest to the largest, developments in our understanding of seismic hazard and forecasting, and the impact of earthquakes on people and the built environment. **Kit Chambers** (University of Bristol) showed what can be achieved by combining high-resolution data with state-of-the-art computing and processing (figure 3). Monitoring and locating microearthquakes induced by oil production is often difficult because of high noise levels, but by combining high-resolution data from large arrays of sensors with advanced processing techniques and computing power, it becomes possible using a migration style approach. Subglacial dynamics can also be investigated using seismological techniques, as **Andy Smith** (British Antarctic Survey) showed (figure 4). Seismic stations deployed on a fast-flowing Antarctic ice stream have been used to monitor seismic events originating at the glacier bed and showed that the movement of a glacier due to the presence of melt water is associated with a high number of seismic events. Swarms of repeating identical events lasting several hours are observed and there is also evidence of seismic anisotropy.

A review and reassessment of earthquake depths, crustal thickness and geothermal calculations presented by **James Jackson** (University of Cambridge) shows that the distribution of seismicity in the lithosphere can be explained fairly simply. His results indicate that the mantle is seismogenic at temperatures less than 600 °C and that although it is usually only the upper continental crust that is seismogenic (up to 350 °C), it can be seismogenic at temperatures up to 600 °C under the dry granulite conditions (high temperature metamorphism of deep crustal rocks) that are associated with continental shield.

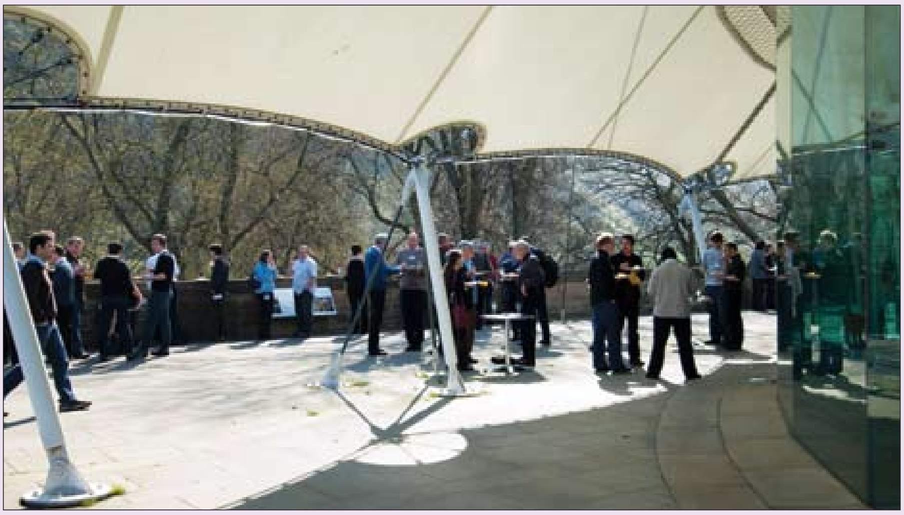
The Sumatran subduction zone is where the Indian plate dives beneath the Asian plate. The 2004 Aceh–Andaman earthquake and the 2005 Nias earthquake highlighted the devastating potential of the massive events that can occur here. **Frederik Tilmann** (University of Cambridge) presented a study of the transition between stable (seismogenic) and creeping behaviour of the northern Sumatran trench using recordings of aftershocks from the 2005 Nias earthquake. The results show that aftershock activity is confined to a relatively narrow zone between the regions of coseismic slip and afterslip (or postseismic slip), and tends to occur on the main fault, not splay structures. The seismic efficiency of afterslip varies strongly along-strike with greater potential for seismic afterslip in regions where coseismic slip was low.

It is widely believed that meaningful earthquake prediction is not possible, but forecasting offers more potential for reducing vulnerability to earthquakes. Also presenting results from the Sumatran subduction zone, **John McCloskey** (University of Ulster) showed that using a variety of data such as coral palaeogeodesy and the slip distribution of past events, it is possible to make falsifiable forecasts of large and potentially devastating earthquakes. These models are by no means simple and John pointed out that we are limited by our understanding of the physical processes in fault zones. Furthermore, there is the significant challenge of disseminating this information effectively to local communities.

**Ian Main** (University of Edinburgh) addressed the question of scale invariance for small and large earthquakes, which has important implications for seismic hazard assessment. Using a global dataset and after correcting for potential sources of statistical bias, Ian showed that mega-earthquakes continue to follow the Gutenberg–Richter trend of smaller earthquakes with no (as yet) observable cut-off or characteristic extreme event.

Estimating ground motions from future earthquakes is vital for seismic hazard assessment but can be problematic in low seismicity regions, such as the UK, where there are relatively few observations. Using data from Japan, **Andreas Rietbrock** (University of Liverpool) showed that it is possible to model ground motion from large earthquakes using source parameters from smaller earthquakes. However, the method requires a good understanding of attenuation, the geometric spreading of the seismic waves and the effect of the near-surface geology at the recording station. The latter are most problematic and the results shown are based on borehole seismic data only. In terms of ground motion measures, engineers are often concerned with peak ground acceleration (PGA). It is well-known that small earthquakes can generate high PGAs but that their short duration means that they are unlikely to be significant from an engineering point of view. An alternative measure, cumulative absolute velocity (CAV), correlates better with damage. Using the UK as an example, **Roger Musson** (British Geological Survey) showed that by using CAV in seismic hazard assessment and setting a threshold value below which ground motion is assumed to be insignificant, these small undamaging ground motions

## "Let's do it again!"

Feedback from participants' questionnaires made it clear that the opportunity to hear about activity in other fields and in industry and the chance to make and reinforce contacts with researchers was widely appreciated. This sort of contact – focused but not overly specialist – should enable UK geophysicists to work more effectively in future. Participants at Edinburgh clearly want this meeting to happen again, and a two-yearly meeting was identified as most likely to be productive.

can be "filtered" from the hazard results.

As an earthquake engineer, **Tiziana Rossetto** (University College London) works at the interface between earthquakes and the built environment. Tiziana presented two examples of multidisciplinary research projects that are aiming to reduce earthquake risk. The first aims to understand the loading effect of tsunamis on buildings using earthquake engineering principles and a new type of tsunami generator in order to provide design guidance for coastal structures (figure 5). The second project investigates why earthquake mitigation measures are not always implemented and how our understanding of human responses to risk may hold the key to more effective implementation.

## Seismology in the UK

**Brian Baptie** (British Geological Survey) gave an overview of what is known about the crust and upper mantle in Britain and presented the results of several recent investigations. He identified a need for better resolution, a 3D velocity model for Britain, and better understanding of the origin of mantle anomalies. The distribution of earthquakes in the UK is well-known but a greater understanding of the forces driving seismicity in this region is required, particularly to refine seismic hazard models. The ongoing development of the UK seismic monitoring network will facilitate this, as would more targeted deployment of dense temporary networks and onshore controlled source experiments.

The UK will contribute to EPOS (European Plate Observing System), a recently announced European Research Infrastructure initiative to coordinate maintaining networks, natural and experimental laboratories, and distributed computational facilities in support of geoscience research. EPOS will build on the work carried out in NERIES (Network of Research Infrastructures in European Seismology).

## Crossing frontiers

Over the two days, an exciting picture of scientific research emerged and the summary given here is merely a snapshot of the enormous amount of work that was presented. One result of the meeting is that we now have an "inventory" of current seismological research within the UK since most of the community was represented (although it is important to note that some key groups, for example those involved in satellite remote sensing, were not in attendance). There was community recognition of the need to increase the visibility of our research so that it gains appropriate priority, particularly in the development of the NERC Earth System Science and Natural Hazards theme action plans.

The theme of the meeting was "frontiers" and we invited presenters to give their impressions of where the frontiers in their particular discipline lie. Several themes emerged. First, the importance of better data was identified as a priority in all fields, which result in better resolution and better models. Secondly, use of technological and computational advances are key to progress, as particularly illustrated by the industrial participants. Thirdly, as we seek to interpret the increasingly detailed images of the Earth's structure that are emerging, greater integration with other fields – mineral physics for example – is required to increase understanding. By crossing such boundaries, new research frontiers will likely come into view.

An overarching theme of the meeting was the importance of interdisciplinary working both for tackling multidisciplinary problems such as seismic risk reduction or for finding novel ways to apply existing knowledge. This requires that diverse groups communicate across working boundaries and one achievement of the meeting was to bring together groups of researchers who do not normally work together, or attend the same conferences, or even speak the same technical language in some cases. Nevertheless, awareness and understanding of what others are doing is vital, and with NERC's Next Generation Science for Planet Earth placing greater emphasis on interdisciplinary collaborative working, this is more important than ever. ●

*Susanne Sargeant (slsa@bgs.ac.uk), Lars Ottemöller and Brian Baptie, British Geological Survey, Murchison House, Edinburgh; Andy Bell, Andrew Curtis and Ian Main, University of Edinburgh.* *The success of the meeting is due to the efforts of a large number of BGS staff, Julian Bukits in particular. We also acknowledge the support of our sponsors, Guralp Systems Ltd and ExxonMobil.*

**Further information**

**Frontiers of Seismology website**:
http://www.earthquakes.bgs.ac.uk/seis09

## Seismology mailing list

To facilitate discussion between UK scientists with interests in seismological research, we have set up a mailing list: seismology@jiscmail.ac.uk